

# SPECIFICATION

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## **INDEPENDENT BRAKING AND CONTROLLABILITY CONTROL METHOD AND SYSTEM FOR A VEHICLE WITH REGENERATIVE BRAKING**

### Field of Invention

[0001] The present invention relates generally to vehicle braking and controllability control systems, commonly referred to as stability control systems, and specifically to a braking and controllability control method and system for a vehicle with regenerative braking that optimizes energy recovery while reducing vehicle oversteer and understeer by providing braking control for individual non-regenerative braking wheels.

### Background of Invention

[0002] The need to reduce fossil fuel consumption and emissions in automobiles and other vehicles predominately powered by internal combustion engines (ICEs) is well known. Vehicles powered by electric motors attempt to address these needs. Another alternative solution is to combine a smaller ICE with electric motors into one vehicle. Such vehicles combine the advantages of an ICE vehicle and an electric vehicle and are typically called hybrid electric vehicles (HEVs). See generally, U.S. Pat. No. 5,343,970 to Severinsky.

[0003] The HEV is described in a variety of configurations. Many HEV patents disclose systems where an operator is required to select between electric and internal combustion operation. In other configurations, the electric motor drives one set of wheels and the ICE drives a different set.

[0004] Other, more useful, configurations have developed. For example, a series hybrid electric vehicle (SHEV) configuration is a vehicle with an engine (most typically an ICE) connected to an electric motor called a generator. The generator, in turn, provides electricity to a battery and another motor, called a traction motor. In the SHEV, the traction motor is the sole source of wheel torque. There is no mechanical connection between the engine and the drive wheels. A parallel hybrid electrical vehicle (PHEV) configuration has an engine (most typically an ICE) and an electric motor that work together in varying degrees to provide the necessary wheel torque to drive the vehicle. Additionally, in the PHEV configuration, the motor can be used as a generator to charge the battery from the power produced by the ICE.

[0005] A parallel/series hybrid electric vehicle (PSHEV) has characteristics of both PHEV and SHEV configurations and is sometimes referred to as a "split" parallel/series configuration. In one of several types of PSHEV configurations, the ICE is mechanically coupled to two electric motors in a planetary gear-set transaxle. A first electric motor, the generator, is connected to a sun gear. The ICE is connected to a carrier gear. A second electric motor, a traction motor, is connected to a ring (output) gear via additional gearing in a transaxle. Engine torque can power the generator to charge the battery. The generator can also contribute to the necessary wheel (output shaft) torque if the system has a one-way clutch. The traction motor is used to contribute wheel torque and to recover braking energy to charge the battery. In this configuration, the generator can selectively provide a reaction torque that may be used to control engine speed. In fact, the engine, generator motor and traction motor can provide a continuous variable transmission (CVT) effect. Further, the HEV presents an opportunity to better control engine idle speed over conventional vehicles by using the generator to control engine speed.

[0006] The desirability of combining an ICE with electric motors is clear. There is great potential for reducing vehicle fuel consumption and emissions with no appreciable loss of vehicle performance or driveability. The HEV allows the use of smaller engines, regenerative braking, electric boost, and even operating the vehicle with the engine shutdown. Nevertheless, new ways must be developed to optimize the HEV's potential benefits.

[0007] One such area of HEV development is optimizing the braking and stability system of the HEV or any other type of vehicle using regenerative braking technology. Regenerative braking (regen) captures the kinetic energy of the vehicle as it decelerates. In conventional vehicles, kinetic energy usually dissipates as heat in a vehicle's brakes or engine during deceleration. Regen converts the captured kinetic energy through a generator into electrical energy in the form of a stored charge in a vehicle's battery. This stored energy is later used to power the electric motor. Consequently, regen also reduces fuel usage and emission production. In certain vehicle configurations, the engine can be disconnected from the rest of the powertrain thereby allowing more of the kinetic energy to be converted into stored electrical energy.

[0008] On most vehicles with regenerative braking, the regenerative braking torque is applied to, or predominantly to, the wheels of only one axle. When regenerative braking is applied to the wheels of only one axle, non-regenerative braking methods may be used at the wheels of the other axles. The desire to recover energy through regenerative braking can result in different braking torques being applied to the wheels of the different axles. The difference between the braking torques can cause unbalanced braking that may degrade vehicle controllability. Degraded controllability can be in the form of either reduced stability or reduced steerability. For example, when excessive regenerative braking torque is applied at the front axle, such as a front wheel drive vehicle, the ability of the front wheels to steer the vehicle may be reduced. The reduced steerability is a condition known as understeer. When excessive regenerative braking torque is applied at the rear axle, for rear wheel drive vehicles, the lateral friction of the rear tires may be reduced. The reduced stability is a condition known as oversteer. Both of these effects, understeer due to excessive levels of regenerative braking at the front axle and oversteer due to excessive levels of regenerative braking at the rear axle, can become greater on low friction surfaces such as ice and snow. The requirement for controllability on low friction surfaces typically forces regenerative braking levels to be reduced, resulting in a corresponding loss of energy recovery.

[0009] There are HEV patents directed to control of regenerative braking functions in various driving conditions. Koga et al. (U.S. Pat. No. 6,033,041) describes a

regenerative braking control system for an electric vehicle where the regenerative braking varies as a function of vehicle inclination. Okamatsu (U. S. Pat. No. 4,335,337) describes a control system for an electric powered vehicle. This invention attempts to improve tire grip performance by adjusting the frequency of the rotations of the induction motors based on the slip frequency of the vehicle without regard to regenerative braking.

[0010] Ohtsu et al., (U.S. Patent No. 5,476,310) also attempts to improve braking performance through the cooperation of mechanical anti-lock brakes and regenerative braking. This invention regulates excessive braking force and slip with a controller using a predetermined slip ratio. Other inventions also attempt to regulate excessive slip. See Asa et al. (U.S. Patent No. 5,654,887) and Kidston et al. (U.S. Pat. No. 5,615,933). Unfortunately, while these inventions do reduce excessive slip, they do not provide an adequate level of stability because they focus mainly on the maximization of straight line stopping.

[0011] Asanuma et al. (U.S. Patent No. 5,318,355), describes a switchover mode from a regenerative or friction braking mode of operation. Unfortunately, this invention is susceptible to false activation of the mode switchover.

[0012] Thus, the ability to distribute brake torque between regenerative and non-regenerative braking while optimizing energy recovery and vehicle controllability constitutes an unmet need in the art.

## Summary of Invention

[0013] Accordingly, the present invention provides a method and system to control braking and improve controllability of a vehicle equipped with regenerative braking. The invention can provide regenerative braking while reducing understeer and oversteer while not significantly reducing energy recovery, even on low friction surfaces. The invention detects vehicle oversteer and understeer and correspondingly balances regenerative braking torque with conventional non-regenerative braking torque if controllability decreases.

[0014] In accordance with an important aspect of the present invention regenerative braking is provided to the wheels of at least one axle, either on a front or a rear axle.

Also, mechanical friction or other non-regenerative brakes of a type known in the art are connected to the wheels of at least one axle, with the regenerative braking and non-regenerative brakes being on different axles. The vehicle has a controller having the microprocessor hardware and software to receive and evaluate sensor input of brake position and wheel speed of each wheel and to activate a generator motor which varies non-regenerative and regenerative braking in optimum proportions among each non-regenerative braking wheel for maximum energy recovery. Further, the controller determines vehicle controllability based on at least one actual vehicle controllability value and at least one predetermined target value. The controller activates a generator motor that operates to reduce regenerative braking, while proportionally increasing non-regenerative braking in order to maintain the actual vehicle controllability value within the predetermined target value.

[0015] In accordance with a related aspect of the invention, the controller can be a simple proportional-integral-derivative feedback type controller.

[0016] The invention can reduce oversteer in vehicle configurations where the front axle wheels are steerable. In a preferred configuration the generator motor provides regenerative braking to the wheels on the rear axle, while the non-regenerative brakes are connected to the wheels on the front axle. The sensor input also includes data showing the steering angle in degrees left or right of dead center. Sensors also provide data related to lateral acceleration and yaw rate.

[0017] Vehicle controllability determinations, such as oversteer, can include measurement and feedback showing wheel longitudinal wheel slip ratio, tire slip angle, and yaw rate. Steering angle can be determined from steering wheel position, steerable wheel position or a time-filtered determination of steering angle. The present invention can also be configured to reduce understeer in front wheel drive vehicles. As regenerative braking is reduced, non-regenerative braking is increased.

[0018] For a rear wheel drive vehicle, where non-regenerative braking is provided on the front wheels, as regenerative braking in the rear is reduced and the vehicle is in a turn commanded by the operator, the non-regenerative braking for the outside wheel of the turn is increased to reduce oversteer. Since non-regenerative braking is only increased on one wheel, a smaller reduction in the amount of regenerative braking is

required. A similar strategy can be used for a front wheel drive vehicle. Here, as regenerative braking is reduced on the front wheels to reduce understeer, the strategy proportionally increases the non-regenerative braking on the rear wheel that is on the inside of the turn. These strategies maximize energy recovery.

[0019] Other objects and features of the present invention will become more apparent to persons skilled in the art to which the present invention pertains from the following description and claims taken in conjunction with the accompanying figures.

### Brief Description of Drawings

[0020] The foregoing objects, advantages, and features, as well as other objects and advantages, will become apparent with reference to the description and figures below, in which like numerals represent like elements and in which:

[0021] Figure 1 illustrates a general hybrid electric vehicle (HEV) configuration.

[0022] Figure 2 illustrates a braking and controllability control strategy of the present invention.

### Detailed Description

[0023] The present invention relates to electrically propelled vehicles such as electric vehicles (EVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) that have a regenerative braking system. The present invention is a system to continuously control braking and controllability for a vehicle with regenerative braking. Figure 1 demonstrates just one possible configuration, specifically a parallel/series hybrid electric vehicle (split) configuration with rear wheel drive. The present invention can easily be modified to adapt to a front wheel drive vehicle.

[0024] In a basic HEV, a planetary gear set 20 mechanically couples a carrier gear 22 to an engine 24 via a one-way clutch 26. The planetary gear set 20 also mechanically couples a sun gear 28 to a generator motor 30 and a ring (output) gear 32. The generator motor 30 also mechanically links to a generator brake 34 and is electrically linked to a battery 36. A traction motor 38 is mechanically coupled to the ring gear 32 of the planetary gear set 20 via a second gear set 40 and is electrically linked to the battery 36. The ring gear 32 of the planetary gear set 20 and the traction motor 38

are mechanically coupled to drive wheels (rear wheels) 42 via an output shaft 44 that is mechanically coupled to a rear axle 66. For purposes of illustration, the vehicle can also have a separate pair of non-driven steerable wheels (front wheels) 64 connected by a front axle 68. The non-driven steerable wheels 64 are positioned toward the front of the vehicle while the drive wheels 42 are positioned toward the rear of the vehicle.

[0025] The planetary gear set 20, splits the engine 24 output energy into a series path from the engine 24 to the generator motor 30 and a parallel path from the engine 24 to the drive wheels 42. Engine 24 speed (or RPM) can be controlled by varying the split to the series path while maintaining the mechanical connection through the parallel path. The traction motor 38 augments the engine 24 power to the drive wheels 42 on the parallel path through the second gear set 40. The traction motor 38 also provides the opportunity to use energy directly from the series path, essentially running off power created by the generator motor 30. This reduces losses associated with converting energy into and out of chemical energy in the battery 36 and allows all engine 24 energy, minus conversion losses, to reach the drive wheels 42.

[0026] A vehicle system controller (VSC) 46 controls many components in this HEV configuration by connecting to each component's controller. An engine control unit (ECU) 48 can connect to the engine 24 via a hardwire interface. All vehicle controllers can be physically combined in any combination or can stand as separate units. They are described as separate units here because they each have distinct functionality. The vehicle controllers have the microprocessor hardware and software to receive and evaluate sensor input and respond according to that input. The VSC 46 communicates with the ECU 48, as well as a battery control unit (BCU) 50 and a transaxle management unit (TMU) 52 through a communication network such as a controller area network (CAN) 54. In this illustration, the BCU 50 connects to the battery 36 via a hardwire interface. The TMU 52 controls the generator motor 30 and traction motor 38 via a hardwire interface.

[0027] Further, the VSC 46 can communicate with an electric hydraulic braking unit (EHBU) 56 through the CAN 54. The EHBU 56 is connected to non-regenerative brakes 58 that ultimately are connected to the vehicle non-driven steerable wheels 64. The

EHBU 56 can control anti-lock braking systems (ABS), regenerative braking, traction control, and non-regenerative braking. In the present invention, braking control for each drive wheel 42 and non-driven steerable wheel 64 is independently available.

[0028] The VSC 46 can receive input from various vehicle component sensors. In accordance with an embodiment of the present invention inputs are provided by: a brake position sensor 62 (such as a brake pedal); wheel speed sensors 70, steerable wheel position sensors 72, and inertial sensors 74. The inertial sensors 74 can measure, for example, lateral acceleration and/or yaw rate. The brake position sensor 62 output can be sent to the VSC 46 or the EHBU 56 depending on vehicle configuration. For the present illustration, the brake position sensor 62 output is sent to the EHBU 56. Wheel speed sensors 70 are located at each vehicle wheel. Steerable wheel position sensors 72 can detect left and right wheel position in degrees deviation from dead center. In other words, the sensors detect the degree of steering angle deviation right or left of a straight ahead direction of travel by the vehicle.

[0029] As stated above, most vehicle configurations with regenerative braking apply braking torque to the wheels of one axle (or predominately to the wheels of one axle). When regenerative braking is applied to the wheels of only one axle, conventional non-regenerative braking methods can be used at the wheels of the other axles to balance the vehicle's overall braking torque. To demonstrate this in the vehicle configuration in Figure 1, the EHBU 56 could command regenerative braking at the drive wheels 42 of the rear axle 66. The EHBU 56 could concurrently command the application of the non-regenerative brakes 58 to the non-driven steerable wheels 64 of the front axle 68. In this example optimal regenerative energy is not realized because any braking torque using non-regenerative brakes 58 results in kinetic energy wasted as heat. Ideally, maximum energy recovery would occur with complete regenerative braking.

[0030] A challenge to obtaining maximum energy recovery through regenerative braking is due to unbalanced braking torques between the front and rear wheels, which can affect vehicle controllability. For example, in a front wheel drive (FWD) vehicle, if excessive braking torque is applied to the front steerable wheels of the front axle (i.e., less non-regenerative braking force is applied to the wheels on the rear axle), the



ability to steer the steerable wheels is reduced (understeer). In a rear wheel drive vehicle (RWD), when excessive braking torque is applied at the drive wheels 42 of the rear axle 66 (e.g., less non-regenerative braking force is applied to the front non-driven steerable wheels 64), the lateral friction of the drive wheels 42 is reduced (oversteer). These controllability problems can become more severe on low friction surfaces such as ice and snow.

[0031] The present invention provides a method and apparatus wherein a braking and controllability control system is provided for each wheel that is configured for non-regenerative braking in a vehicle also equipped with regenerative braking, such as the configuration illustrated in Figure 1.

[0032] In the case of a FWD vehicle (not shown), regenerative braking is usually applied at the front axle but will tend to reduce steering responsiveness. When steering responsiveness drops below the desired level, as determined by any combination of the measured indicators: tire slip angle, yaw rate, and longitudinal wheel slip ratio, regenerative braking torque will be reduced in accordance with the invention and replaced by non-regenerative braking torque at the rear wheels based on the operation of a closed loop controller. This transfer of braking torque will reduce the front biased brake imbalance and correspondingly improve steering responsiveness. The amount of brake torque that must be transferred to the rear axle can be minimized by applying all of the transferred non-regenerative torque to the rear wheel that travels toward the inside of a curved path that is to be followed by the vehicle. The application of braking torque on only the inside rear wheel creates a moment tending to rotate the vehicle in the direction of the turn, thus reducing understeer.

[0033] In the case of a RWD vehicle, regenerative braking will be applied at the rear axle 66 and will tend to reduce vehicle stability, causing oversteer. When vehicle stability drops below the desired level, as determined by a combination of the indicators: tire slip angle, yaw rate, and longitudinal wheel slip, regenerative braking torque will be reduced and replaced by non-regenerative braking torque at the front non-driven steerable wheels 64 based on the operation of a closed loop controller. This transfer of braking torque reduces the rear biased brake imbalance and correspondingly

improves vehicle stability. The amount of brake torque that must be transferred to the front axle 68 can be minimized by applying all of the transferred non-regenerative torque to the non-driven steerable wheel 64 that travels toward the outside of a curved path followed by the vehicle. The application of non-regenerative braking torque on only the outside non-driven steerable wheel 64 will create a moment that will tend to counter the rotation of the vehicle, thus reducing oversteer.

[0034] The invention can provide regenerative braking while reducing vehicle understeer and oversteer even on low friction surfaces while not significantly reducing energy recovery. The controller of the present invention can be physically located either within the VSC 46 or as a stand-alone unit, such as the EHB 56. The controller continuously monitors vehicle controllability and correspondingly commands a change in regenerative braking in real time if vehicle controllability is reduced.

[0035] During a braking event, the present invention preferably initially relies on regenerative braking, while continuously monitoring vehicle controllability and adjusts braking accordingly. The system attempts to correct control problems by maintaining vehicle controllability within a predetermined target value. This means that the system of the present invention should react before conventional stability control or anti-lock braking systems engage.

[0036] To achieve the goal of improvement of vehicle controllability, objectives of the present invention are to monitor the development of any lateral instability (such as oversteer or high longitudinal wheel slip ratio) and reduce regenerative braking to achieve a more conservative brake balance. Longitudinal wheel slip ratio is determined by measuring the speed of the front wheels and the rear wheels using wheel speed sensors 70. A formula for longitudinal wheel slip ratio is:

[0037]

$$\text{Longitudinal Wheel Slip Ratio} = 1 - \frac{\text{Vehicle Speed} - \text{Wheel Speed}}{\text{Vehicle Speed}}$$

[0038]

As a first approximation of vehicle speed, the wheel speed of the front wheels can be used for a rear wheel drive vehicle and the wheel speed of the rear wheels can be used for a front wheel drive vehicle. When rear wheel brakes are applied, vehicle deceleration comes from the rear wheels. For example, a ten percent (10%)

longitudinal wheel slip ratio means the rear wheels are traveling ten percent (10%) slower than the vehicle. As the longitudinal wheel slip ratio increases for the rear wheels, lateral stability decreases.

[0039] The present invention uses feedback control algorithms to monitor and dynamically modify front and rear braking torque to initiate braking based on driver demand that initially favors regenerative braking more than conventional braking balance would indicate while monitoring and maintaining vehicle controllability. For a rear wheel drive vehicle, oversteer can be reduced and for a front wheel drive vehicle, understeer can be reduced.

[0040] Figure 2 illustrates one possible configuration of the present invention by way of a block diagram of the regenerative braking controller utilizing features of the present invention. As stated above, this controller can be housed within the VSC 46 or a separate controller, such as the EHB 56. This controller can generally include a simple proportional-integral-derivative feedback controller. The strategy illustrated in Figure 2 can be used for a two-wheel drive, rear wheel drive vehicle with regenerative braking applied, or predominately applied, to the rear wheels. With minor modifications, one skilled in the art could easily adapt this strategy for a front wheel drive vehicle. For the determination of vehicle controllability, such as oversteer and understeer, the strategy can continuously monitor longitudinal wheel slip ratio, tire slip angle, and yaw rate individually or in any combination. For purposes of illustration, the strategy presented in Figure 2 presents all three methods to monitor vehicle oversteer and understeer. The strategy of Figure 2 can also continuously adjust the proportion of regenerative and non-regenerative braking to optimize energy recovery while maintaining the actual vehicle controllability within predetermined controllability target values. This can be accomplished using separate controllers to increase braking for each of the non-regenerative braking wheels.

[0041] In Figure 2, the illustrated strategy starts with each "key-on" event and ends with each "key-off" event. The strategy once initiated at step 90 can monitor several vehicle inputs from the wheel speed sensors 70, steerable wheel position sensors 72 and brake position sensor 62.

[0042] After step 90, the strategy proceeds to step 92 and determines whether the

vehicle operator has demanded a steering angle to the right or left off dead center (i.e., a turn). For this illustrated strategy, a steering angle off dead center determination is made using input from the steerable wheel position sensors 72. In an alternate embodiment, a steering wheel position sensor (not shown) could also be used for this determination. The steering angle could also include a time filtered value of a steering angle. If no at step 92, the strategy proceeds to step 88 and sets target tire slip angle and yaw rate to "0" then proceeds to step 96. If yes at step 92, the strategy proceeds to step 94. At step 94, the strategy calculates a target tire slip angle and target yaw rate (turn rate) using the steering angle and vehicle speed input from the wheel speed sensors 70 and proceeds to step 96.

[0043] At step 96, the strategy determines whether a braking force has been commanded. A braking force command can come from the vehicle operator or from the VSC 46. A braking force can be requested by the vehicle operator where the braking force to be applied to the vehicle wheels is determined using input from the brake position sensor 62 and the vehicle applies braking force in relation to the position of the brake position sensor 62. A braking force can also be requested by the VSC 46, such as to simulate the engine braking during coast-down of a traditional ICE only vehicle. If no, the strategy cycles back to step 90. If yes, the strategy proceeds to step 98.

[0044] At step 98, the strategy commands braking torque using regenerative braking, or predominately regenerative according to the braking command. For the present illustration, regenerative braking would be applied to the rear axle drive wheels 42. In an alternate embodiment having a front wheel drive configuration, the strategy would apply regenerative braking to the front wheels. Next, the strategy proceeds to step 100 to determine: wheel speed for the drive wheels 42 on the rear axle 66 and the non-driven steerable wheels 64 on the front axle 68, lateral acceleration and yaw rate. These determinations can be obtained using various vehicle inputs such as wheel speed sensors 70 and inertial sensors 74 known in the art. The strategy then proceeds to step 102.

[0045] At step 102, the strategy calculates longitudinal wheel slip ratios (as described above) and then proceeds to step 104 to make determinations of whether vehicle

controllability indicators are within predetermined threshold values.

[0046] At step 104, the strategy determines whether the calculated slip ratio of step 102 exceeds a predetermined wheel slip ratio value. For this illustration, a longitudinal wheel slip ratio value of ten percent (10%) is used, but a preferred longitudinal wheel slip ratio value is five percent (5%). The predetermined longitudinal wheel slip ratio value can also be a dynamic variable that is dependent on vehicle operating conditions.

[0047] If yes at step 104, the strategy proceeds to step 106 and determines whether the vehicle is turning using input from vehicle sensors and driver demand, such as steerable wheel position sensors 72 and inertial sensors 74. If yes, the strategy proceeds to step 112 and commands application of the non-regenerative brakes 58 on the non-driven steerable wheel 64 of the front axle 68 positioned on the outside of the turn and the proportional reduction of regenerative braking on the drive wheels 42 of the rear axle 66 to balance braking torque until the vehicle is within predetermined thresholds for controllability. Overall braking force remains the same or consistent with braking command. Only the proportion of regenerative braking is reduced.

[0048] In an alternate FWD configuration using the strategy of the present invention, the strategy would command application of the non-regenerative brakes on the wheel of the rear axle positioned on the inside of the turn and the proportional reduction of regenerative braking on the wheels of the front axle to balance braking torque until the vehicle is within predetermined thresholds for controllability.

[0049] If no at step 106, the strategy proceeds to step 114 and commands application of the non-regenerative brakes 58 on the non-driven steerable wheels 64 of the front axle 68 and the proportional reduction of regenerative braking on the drive wheels 42 of the rear axle 66 to balance braking torque until the vehicle is within predetermined thresholds for controllability. Overall braking force remains the same or consistent with the braking command. Only the proportion of regenerative braking is reduced.

[0050] Returning to step 104, if the strategy determines longitudinal wheel slip ratio is not greater than a predetermined value, the strategy proceeds to step 108. At step

108, the strategy determines whether actual tire slip angle exceeds the target tire slip angle. If yes, the strategy proceeds to step 106; if no, the strategy proceeds to step 110.

[0051] At step 110, the strategy determines whether actual yaw rate exceeds the target yaw rate. If yes, the strategy proceeds to step 106; if no, the strategy cycles back to step 90.

[0052] As described in the strategy illustrated in Figure 2, specific calculations need to be developed to obtain target and actual values for wheel longitudinal wheel slip ratio, tire slip angle, or yaw rate to practice the present invention. For a first calculation, the formula for longitudinal wheel slip ratio shown above can be used.

[0053] For a second calculation, tire slip angle is factored to determine a modified tire slip angle. The modified tire slip angle can also determine acceptable vehicle controllability by estimating an alpha, the tire slip angle, and its rate of change, determining a target value of alpha from a tire slip angle determination, and using closed loop control to reduce the level of regenerative braking to the required amount.

[0054] Alpha and its time derivative, alpha\_dot, can be estimated by known methods of calculation using inertial sensors 74. Other methods known in the art can also be used to infer tire slip angle such as Global Positioning System sensors (not shown), optical sensors (not shown), radar (not shown) and other like technologies. If the regenerative braking torque was applied at the rear axle 66 wheels (or primarily at the rear wheels 42) and therefore oversteer was the concern, then alpha and its derivative would be estimated for the rear axle 66 wheels. If the regenerative braking torque was applied to the output shaft 44 at the front axle 68 wheels (or primarily at the front non-driven steerable wheels 64) and therefore understeer was the concern, then alpha and its derivative would be estimated for the front axle 68 wheels. Note that since the front axle 68 wheels are steerable, the calculation of the alpha estimate would also include the steerable wheel position. That would also be true of the rear axle 66 wheels if they were steered.

[0055] Lateral acceleration,  $A_y$ , of the vehicle can be measured or estimated at a location

corresponding to the location of alpha. The target value for alpha,  $\alpha_{\text{target}}$ , is calculated in proportion to the absolute value of  $A_y$  according to the following equation:

[0056]  $\alpha_{\text{target}} = CC * \text{abs}(A_y) + \alpha_{\text{offset}},$

[0057] where  $CC$  is the cornering compliance of the tires at the location of the alpha estimate and  $\alpha_{\text{offset}}$  is a constant compensating for estimation error for alpha. The equation yields a value for  $\alpha_{\text{target}}$  that is always positive. In the above equation, the measured value of  $A_y$  could be replaced by a value determined in some other manner that represented the limit of lateral acceleration corresponding to available surface friction.

[0058] The closed loop control of tire slip angle, alpha, using regenerative braking torque,  $T_{\text{regen}}$ , can be implemented as follows:

[0059]  $T_{\text{correction\_r}} = \max(k_p * (\alpha - \alpha_{\text{target}}) + k_d * \alpha_{\text{dot}}, 0),$

[0060] where  $k_p$  and  $k_d$  are calibratable values;

[0061]  $T_{\text{correction\_l}} = \max(-k_p * (\alpha + \alpha_{\text{target}}) - k_d * \alpha_{\text{dot}}, 0);$

[0062]  $T_{\text{correction}} = \max(T_{\text{correction\_r}}, T_{\text{correction\_l}});$  and

[0063]  $T_{\text{regen}} = T_{\text{desired\_regen}} - T_{\text{correction}}.$

[0064] The above equations are an implementation of a simple proportional-integral-derivative feedback controller based on the assumption that  $T_{\text{regen}}$  and  $T_{\text{desired\_regen}}$  are always positive values. The torque correction,  $T_{\text{correction\_r}}$ , corresponds to a tire slip angle in one direction (a right hand turn) while  $T_{\text{correction\_l}}$  corresponds to the other direction. These equations will act to reduce the level of regenerative braking torque when the tire slip angle exceeds the target level. For the third method, vehicle yaw rate,  $YR$ , is used as the indicator of vehicle controllability. Acceptable vehicle controllability is maintained by measuring the yaw rate, calculating a target value, and using closed loop control to reduce the level of regenerative braking as required to ensure that the yaw rate does not exceed the target value.

[0065] Vehicle yaw rate, YR, would be a signed value. The target value of yaw rate, YR\_target, would be a signed value that is calculated using the methods which are well established in the practice of vehicle stability control. The closed loop control of yaw rate, YR, would be implemented by reducing regenerative braking torque with a correction term, T\_correction, as follows:

[0066]  $T\_correction\_r = \max(kp*(YR - YR\_target) + kd*YR\_dot + ki*YR\_int, 0);$

[0067]  $T\_correction\_l = \max(-kp*(YR - YR\_target) - kd*YR\_dot - ki*YR\_int, 0);$

[0068]  $T\_correction = \max(T\_correction\_r, T\_correction\_l);$  and

[0069]  $T\_regen = T\_desired\_regen - T\_correction,$

[0070] where kp, kd and ki are calibratable values, YR\_dot is the derivative of YR or (YR - YR\_target) and YR\_int is the integral of (YR - YR\_target).

[0071] The above equations are an implementation of a simple proportional-integral-derivative feedback controller.

[0072] The above-described embodiments of the invention are provided purely for purposes of example. Many other variations, modifications, and applications of the invention may be made. Variations could include, but are not limited to, applying the invention to front wheel drive vehicles, rear wheel drive and all-wheel drive vehicles. Additionally variations could include, but are not limited to, applying the invention to front wheel steer vehicles, rear wheel steer vehicles and all-wheel steer vehicles.